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Specification

Processing Apparatus

Background of the Invention

The present invention relates to a processing apparatus for performing processes in an Si-containing atmosphere.

In the manufacture of a semiconductor device, flat panel display, and organic EL (electro luminescent panel) display, plasma processing apparatuses are widely used to perform processes such as formation of an insulating film, e.g., an oxide film, crystal growth of a semiconductor layer, etching, and ashing. A high-frequency plasma CVD apparatus will be described as a prior art example of the plasma processing apparatus. Fig. 6 is a diagram showing the arrangement of the main part of a conventional high-frequency plasma CVD (Chemical Vapor Deposition) apparatus.

The CVD apparatus shown in Fig. 6 includes a process chamber 101 and a plasma source which generates plasma P with high frequency. The chamber 101 accommodates a susceptor 102 for placing a substrate W thereon. The susceptor 102 incorporates a heater 103 which heats the substrate W to a predetermined temperature. An exhaust port 104 is formed in the lower portion of the chamber 101. The chamber 101 is evacuated by a vacuum pump (not shown) communicating

with the exhaust port 104.

The plasma source includes an antenna 121 which supplies high frequency into the chamber 101, and a gas introducing nozzle 111 which introduces source gases into the chamber 101. The antenna 121 is arranged in the upper space in the chamber 101 to oppose the susceptor 102, and is connected to a high-frequency power supply (not shown) through a high-frequency waveguide 124.

When an Si (silicon) thin film is to be formed on the substrate W, the interior of the chamber 101 is evacuated, and the substrate W is heated by the susceptor 102 to about 400°C. Then, as source gases, SiH_4 and SiF_4 are introduced through the gas introducing nozzle 111. When high frequency is supplied from the antenna 121, SiH_4 and SiF_4 dissociate to form SiH_x and SiF_x (x = 1, 2, and 3) radicals. The radicals react on the surface of the substrate W to form an Si thin film (this is described in, e.g., "The 62nd Symposium of the Society of Applied Physics, Digest 14a-ZF-3", September 2001, p.736).

In this manner, radicals are directly concerned in thin film formation using a plasma. This also applies to a process such as etching or ashing.

When the same process is performed with one plasma processing apparatus under the same conditions, however, each time the process is performed, the plasma

state changes, and the process reproducibility is poor. When the same process is performed with different apparatuses under the same conditions, the plasma state differs among the apparatuses, and it is difficult to perform the process with good reproducibility. Consequently, individual substrates W cannot be processed uniformly.

Summary of the Invention

The present invention has been made to solve the above problems, and ahs as its object to improve the process reproducibility.

According to the findings of the inventor of the present invention, when a process is to be performed in an Si-containing atmosphere, to monitor Si is effective in realizing the process with good reproducibility. In particular, Si has an absorption spectrum in an ultraviolet region, and can be measured highly sensitively with a simple method. The present invention has been made based on these findings.

More specifically, the characteristic feature of a processing apparatus according to the present invention resides in comprising a vessel which accommodates a target object, ultraviolet light-generating means for outputting ultraviolet light or vacuum ultraviolet light toward an atmosphere containing radicals in the vessel, ultraviolet

light-receiving means for receiving the ultraviolet light or vacuum ultraviolet light passing through the atmosphere, and analysis control means for obtaining a density of the radicals in the atmosphere on the basis of an output signal from the ultraviolet light-receiving means, to control a process parameter.

The analysis control means may obtain an attenuation amount of the ultraviolet light or vacuum ultraviolet light passing through the atmosphere on the basis of the output signal from the ultraviolet light-receiving means, and obtain the density of the radicals in the atmosphere from the attenuation amount.

The processing apparatus described above may further comprise means for intermittently outputting the ultraviolet light or vacuum ultraviolet light toward the atmosphere and outputting an ultraviolet light presence/absence signal indicating presence/absence of the ultraviolet light or vacuum ultraviolet light, and means for obtaining a difference calculated by subtracting a light reception amount of the ultraviolet light-receiving means obtained when the ultraviolet light or vacuum ultraviolet light is absent from a light reception amount of the ultraviolet light-receiving means obtained when the ultraviolet light or vacuum ultraviolet light is present on the basis of the ultraviolet light presence/absence signal, and obtaining the density of the radicals in the atmosphere from the

difference.

The processing apparatus described above may have means for causing the ultraviolet light or vacuum ultraviolet light output from the ultraviolet light-generating means to pass through a plurality of optical paths and to be received by the ultraviolet light-receiving means. Modulators having modulation frequencies that are different from each other may be arranged to the optical paths respectively.

In the processing apparatus described above, the vessel may have a window through which the ultraviolet light passes, and the window may be heated. Alternatively, the window may have a cylindrical structure.

The processing apparatus described above may further comprise temperature measuring means for measuring a temperature of molecular or atomic radicals in the atmosphere, and the analysis control means may control the process parameter on the basis of the output signal from the ultraviolet light-receiving means and a measurement result of the temperature measuring means.

The temperature measuring means may include laser beam generating means for generating a laser beam toward the atmosphere, laser beam receiving means for receiving the laser beam passing through the atmosphere, and analysis means for obtaining an attenuation amount spectrum of the laser beam passing through the

atmosphere on the basis of an output signal from the laser beam receiving means, and obtaining a temperature of molecular or atomic radicals in the atmosphere from a pattern of the attenuation amount spectrum. Also, the temperature measuring means may further include means for intermittently outputting the laser beam toward the atmosphere and outputting a laser beam presence/absence signal indicating presence/absence of the laser beam, and means for obtaining a spectrum of a difference calculated by subtracting a light reception amount of the laser beam receiving means obtained when the laser ultraviolet beam is absent from a light reception amount of the laser beam receiving means obtained when the laser beam is present on the basis of the laser beam presence/absence signal, and obtaining a temperature of the molecular or atomic radicals in the atmosphere from a pattern of the spectrum.

Alternatively, the temperature measuring means may measure a light emission spectrum of the molecular or atomic radicals in the atmosphere, and may obtain a temperature of the molecular or atomic radicals in the atmosphere from an obtained spectrum pattern.

The processing apparatus described above may have means for causing the laser beam output from the laser beam generating means to pass through a plurality of optical paths, and to be received by the laser beam means. Modulators having modulation frequencies that

are different from each other may be arranged to the optical paths respectively.

In the processing apparatus described above, the vessel may have a window through which the laser beam passes, and the window may be heated. Alternatively, the window may have a cylindrical structure.

In processing apparatus described above, the radicals may be atomic radicals, and may include any one element selected from Si, N, O, F, H, and C.

Brief Description of the Drawings

Fig. 1 is a diagram showing the arrangement of a high-frequency plasma CVD apparatus according to the first embodiment of the present invention;

Fig. 2 is a diagram showing the arrangement of a high-frequency plasma CVD apparatus according to the second embodiment of the present invention;

Fig. 3 is a diagram for explaining an example of a high-frequency plasma CVD apparatus according to the third embodiment of the present invention;

Fig. 4 is a diagram for explaining another example of the high-frequency plasma CVD apparatus according to the third embodiment of the present invention;

Figs. 5A to 5C are graphs for explaining an example of two-dimensional parameter control; and

Fig. 6 is a diagram showing the arrangement of the main part of a conventional high-frequency plasma CVD apparatus.

Detailed Description of the Preferred Embodiments

The embodiments of the present invention will be described in detail with reference to the accompanying drawings. Embodiments in which the present invention is applied to high-frequency plasma CVD apparatuses which form an Si thin film will be described.

First Embodiment

Fig. 1 is a diagram showing the arrangement of a high-frequency plasma CVD apparatus according to the first embodiment of the present invention. A process chamber 1 serving as a processing vessel accommodates a susceptor 2 for placing thereon a glass substrate W as a target object. An electrostatic chuck or mechanical chuck (not shown) to bring the glass substrate W into tight contact with the susceptor 2 is prepared for the susceptor 2. The susceptor 2 incorporates a heater 3 for heating the glass substrate W to a predetermined temperature. The temperature of the heater 3 is changed in accordance with a control signal S5 output from a controller 44 (to be described later). An exhaust port 4 is formed in the lower portion of the chamber 1, and is connected to a vacuum pump 4A. The vacuum pump 4A adjusts the pressure in the chamber 1 in accordance with

a control signal S6 output from the controller 44.

A gas introducing nozzle 11 is arranged in the upper portion of the chamber 1. The nozzle 11 is connected to a gas introducing pipe 13 through a valve 12. The gas introducing pipe 13 is connected to gas supply sources 16A, 16B, and 16C through valves 14A, 14B, and 14C and mass flow controllers (MFCs) 15A, 15B, and 15C, respectively. The gas supply sources 16A to 16C respectively supply SiH_4, H_3, and SiF_4 as source gases. The MFCs 15A to 15C respectively adjust the flow rates of the source gases in accordance with control signals S1 to S3 output from the controller 44.

A disk antenna 21 is arranged in the upper space in the chamber 1 to oppose the susceptor 2. A round ground plate 23 is arranged on the disk antenna 21 through a quartz plate 22. The disk antenna 21 and ground plate 23 are connected to the inner and outer conductors, respectively, of a coaxial waveguide 24. The coaxial waveguide 24 is connected to a high-frequency power supply 26 through a rectangular waveguide 25. The output power of the high-frequency power supply 26 is changed in accordance with a control signal S4 output from the controller 44. The rectangular waveguide 25 or coaxial waveguide 24 is provided with a load matching unit 27.

The CVD apparatus further includes a radical density measuring means employing absorption

spectroscopy. Absorption spectroscopy is a method of measuring the absolute density of atoms or molecules with a predetermined level contained in a plasma on the basis of the attenuation amount of light passing through the plasma by utilizing the fact that the light absorption wavelength changes depending on the level of the atoms or molecules. With this method, the density of Si radicals can be measured easily at high sensitivity.

The radical density measuring means according to this embodiment includes a hollow cathorde lamp (HCL) 41 arranged outside the chamber 1, an input light guide 41A for connecting the hollow cathode lamp 41 and chamber 1, a chopper (modulator) 45 provided to the input light guide 41A, an ultraviolet light-receiving section 42 arranged outside the chamber 1, an output light guide 42A for connecting the ultraviolet light-receiving section 42 and chamber, and a radical density calculating section 43 electrically connected to the output of the ultraviolet light-receiving section 42.

The input light guide 41A and output light guide 42A are arranged on one straight line intersecting the central axis of the chamber 1. The heights of the input light guide 41A and output light guide 42A are set in accordance with the height of a plasma P generated between the disk antenna 21 and susceptor 2.

The hollow cathode lamp 41 operates as an

ultraviolet light-generating section which outputs ultraviolet light UV having Si radical absorption wavelengths of 288.2 nm and 251.6 nm. In the plasma, the two wavelengths can be utilized. In a process of extracting Si radicals generated by the plasma, however, only 251.6 nm can be utilized. The former case also has a better sensitivity with 251.6 nm. A ring dye laser oscillator may be used in place of the hollow cathode lamp 41.

The chopper 45 pulse-modulates the ultraviolet light UV output from the hollow cathode lamp 41. The chopper 45 outputs to the ultraviolet light-receiving section 42 a trigger signal (ultraviolet light present/absent signal) S10 synchronized with the ON/OFF operation of the pulse-modulated ultraviolet light UV.

The ultraviolet light-receiving section 42 receives the ultraviolet light UV output from the chamber 1. The ultraviolet light-receiving section 42 discriminates light received when the ultraviolet light UV is present (ON state) and light received when the ultraviolet light UV is absent (OFF state) from each other on the basis of the trigger signal S10 input from the chopper 45. The ultraviolet light-receiving section 42 calculates the difference obtained by subtracting the light reception amount obtained when the ultraviolet light UV is absent from the light reception amount obtained when the ultraviolet light UV is present, and

outputs the resultant value to the radical density calculating section 43. While the process gas is not introduced and the plasma P is not generated, the light reception amount of the ultraviolet light UV is measured in advance and set in the radical density calculating section 43, prior to the process, as the light emission amount of the ultraviolet light UV.

The radical density calculating section 43 calculates the attenuation amount of the ultraviolet light UV passing through the plasma on the basis of the light emission amount of the ultraviolet light UV input in advance and the output signal from the ultraviolet light-receiving section 42, to calculate the density of the Si radicals contained in the plasma P from the attenuation amount, and outputs the calculated density to the controller 44.

The controller 44 controls parameters for plasma generation so that the radical density calculated by the radical density calculating section 43 becomes close to a preset value. More specifically, the controller 44 outputs the control signal S6 to the vacuum pump 4A to control the gas pressure in the chamber 1. The controller 44 also outputs the control signals S1 to S3 to the MFCs 15A to 15C, respectively, to control the adjustment of their flow rates. The controller 44 outputs the control signal S4 to the high-frequency power supply 26 to control the output

power. The controller 44 also outputs the control signal 5 to the power supply of the heater 3 to control the temperature of the heater 3, thus adjusting the temperature of the susceptor 2.

The radical density calculating section 43 and controller 44 form an analysis control means. The analysis control means includes a computer and has an arithmetic processing unit, storage, operation unit, and input/output interface unit. The storage stores measurement data, data necessary for calculating the radical density, and a control program. The arithmetic processing unit calculates the radical density in accordance with the control program, and controls the operation of the entire apparatus as will be described later. Data can be input from the operation unit. When the input/output interface unit is connected to another management system or the like, the analysis control means can communicate with it.

The control reference value may be set outside the apparatus, or may be acquired by the apparatus itself. When the control reference value is to be set outside the apparatus, for example, it is set from the operation unit by the operator, or from a central control unit via the input/output interface unit. When the control reference value is to be acquired by the apparatus itself, for example, a value obtained after the lapse of a specific period of time since the start

of the process is set as the reference value. If there is a preprocess, the value obtained in the preprocess is set as the reference value.

Ultraviolet light transmission windows 5A and 5B made of quartz are respectively formed at the distal ends of the light guides 41A and 42A, that is, the boundary of the interiors of the input light guide 41A and chamber 1 and that of the interiors of the output light guide 42A and chamber 1. If a pollutant that absorbs the ultraviolet light UV attaches to the transmission windows 5A and 5B, an error occurs in the measurement result of the radical density. In order to prevent this, the transmission windows 5A and 5B may be heated to a high temperature of about 200°C to 400°C, so the pollutant may not attach to them easily. Alternatively, the transmission windows 5A and 5B may be formed of capillary plates each having a cylindrical structure with an aspect ratio of 3 or more. The capillary plates may have bottoms.

The operation of the plasma processing apparatus according to this embodiment will be described.

The glass substrate W is arranged on the susceptor 2 and is brought into tight contact with it by an electrostatic chuck or the like. The substrate temperature is set to 400°C with the heater 3. The interior of the chamber 1 is evacuated with the vacuum pump 4A. Source gases are introduced into the chamber 1

from the nozzle 11 with flow rates of $SiH_4/H_2/SiF_4$ = 5/200/30 sccm (standard cubic centimeter/minute) to maintain the pressure in the chamber 1 at 1.5 Pa. In this state, a high frequency with power of 800 W is supplied into the chamber 1. Then, SiH_4 and SiF_4 dissociate to form SiH_x and SiF_x (x = 1, 2, and 3) radicals. These radicals react on the surface of the substrate W to deposit Si.

When performing this process, the density of the Si radicals contained in the plasma (atmosphere) P is measured. First, the hollow cathode lamp 41 outputs ultraviolet light UV having wavelengths of 288.2 nm and 251.6 nm. The chopper 45 pulse-modulates the ultraviolet light UV and outputs it intermittently toward the plasma P in the chamber 1. The ultraviolet light UV passes through the chamber 1 horizontally in the direction of diameter. When the ultraviolet light UV having the wavelengths of 288.2 nm and 251.6 nm pass through the plasma P, it is partly absorbed by the Si radicals contained in the plasma P and reaches the ultraviolet light-receiving section 42.

The ultraviolet light-receiving section 42 discriminates, from the trigger signal S10 based on the ON/OFF states of the ultraviolet light UV input from the chopper 45, light received when the ultraviolet light UV is present (ON state) and light received when the ultraviolet light UV is absent (OFF state) from each

other, and calculates a difference obtained by subtracting the light reception amount obtained when the ultraviolet light UV is absent from the light reception amount obtained when it is present. Thus, background light, e.g., light emitted by the plasma P itself, which is not pertinent to the ultraviolet light UV is removed, and the light reception amount of the ultraviolet light UV can be obtained.

The radical density calculating section 43 obtains the attenuation amount of the ultraviolet light UV on the basis of the light emission amount of the ultraviolet light UV input in advance and the output signal from the ultraviolet light-receiving section 42, and calculates the density of the Si radicals from the attenuation amount. The controller 44 controls the parameters for plasma generation so that the obtained radical density becomes close to the preset value.

Alternatively, the trigger signal S10 may be supplied to the radical density calculating section 43, and the radical density calculating section 43 may perform arithmetic processing to remove the influence of the background light on the ultraviolet light UV.

In this CVD apparatus, plasma generation is controlled by adjusting the gas pressure, the gas mixing ratio, the flow rate of the entire gas mixture, and the high-frequency power, and temperature of the susceptor 2.

When the gas pressure is to be adjusted, the

control signal S6 to be supplied to the vacuum pump 4A is controlled. When the radical density is high, the gas pressure is increased. When the radical density is low, the gas pressure is decreased.

When the gas mixing ratio and the flow rate of the entire gas mixture are to be adjusted, the control signals S1 to S3 to be output to the MFCs 15A to 15C are controlled to adjust the flow rates of SiH_4, H_2, and SiF_4. When the radical density is high, the mixing ratio of SiH_4 to SiF_4 is decreased, or the entire flow rate is decreased. When the radical density is low, the mixing ratio of SiH_4 to SiF_4 is increased, or the entire flow rate is increased.

When the high-frequency power is to be adjusted, the control signal S4 to be output to the high-frequency power supply 26 is controlled. When the radical density is high, the supply power is decreased to suppress plasma generation. When the radical density is low, the supply power is increased to promote plasma generation.

To adjust the temperature of the susceptor 2, the control signal S5 to be output to the power supply of the heater 3 is controlled. When the radical density is high, the temperature of the susceptor 2 is increased to increase the gas temperature, thus suppressing Si deposition. When the radical density is low, the temperature of the susceptor 2 is decreased to decrease

the gas temperature, thus promoting Si deposition.

These control operations are performed by combining proportional control, derivative control, and integral control.

When the radical density is maintained at a constant level in this manner, the process reproducibility is improved, so that a uniform Si thin film can be formed on the individual glass substrates W.

In this embodiment, the ultraviolet light UV is used for measuring the radical density. Alternatively, vacuum ultraviolet light VUV can be used. This also applies to other embodiments to be described later. When the vacuum ultraviolet light VUV is to be used, the interior of the input light guide 41A connected between the hollow cathode lamp 41 and chamber 1 and the interior of the output light guide 42A connected between the ultraviolet light-receiving section 42 and chamber 1 are set at a vacuum state, so that attenuation of the vacuum ultraviolet light VUV can be suppressed.

In this embodiment, the density of the atomic Si radicals is measured. Alternatively, the density of molecular SiH_x and SiF_x ($x = 1$, 2, and 3) radicals may be measured to control parameters for plasma generation. Alternatively, all these density measurements may be performed to control parameters for plasma generation.

Second Embodiment

The volume of the chamber 1 is constant. Under a constant pressure, the density of radicals contained in the plasma P is inversely proportional to the temperature of a gas containing molecular or atomic radicals. For example, the higher the gas temperature, the lower the radical density. Also, the higher the gas temperature, the higher the radical speed. When measuring the radical density by absorption spectroscopy, as the gas temperature increases, the number of radicals appearing on the optical path of the ultraviolet light UV increases. Then, the attenuation amount of the ultraviolet light UV passing through the plasma P increases, so that the radical density is measured to be larger than it actually is. Accordingly, to perform parameter control based on the plasma density more accurately, the gas temperature must be considered. A high-frequency plasma CVD apparatus that has such a function will be described.

Fig. 2 is a diagram showing the arrangement of a high-frequency plasma CVD apparatus according to the second embodiment of the present invention. Fig. 2 shows a section perpendicular to the central axis of a chamber 1. The same constituent elements as those shown in Fig. 1 are denoted by the same reference numerals.

The CVD apparatus according to this embodiment has a gas temperature measuring means in addition to a

radical density measuring means. The molecule level changes in accordance with the temperature. Also, light absorption wavelength changes in accordance with the molecule level. The gas temperature measuring means utilizes these facts to measure the temperature of a gas contained in the plasma on the basis of the attenuation amount of light passing through the plasma. More specifically, the gas temperature measuring means includes a laser beam output section 51 arranged outside the chamber 1, a laser beam receiving section 52, and a gas temperature calculating section (analyzing means) 53.

The laser beam output section 51 sweeps with an output laser beam L having a wavelength of 251.6 nm as the center. As the laser beam output section 51, a ring dye laser oscillator or the like is used. The laser beam L output from the laser beam output section 51 is input to the chamber 1 through a laser beam transmission window 6A formed in the side wall of the chamber 1.

The laser beam receiving section 52 receives the laser beam L output from the chamber 1 through a laser beam transmission window 6B formed in the side wall of the chamber 1, and outputs the light reception amount to the gas temperature calculating section 53. While the process gas is not introduced and the plasma P is not generated, the light reception amount of the ultraviolet light UV is measured in advance and set in

the gas temperature calculating section 53, prior to the process, as the light emission amount of the laser beam L.

The transmission windows 6A and 6B are made of quartz and arranged at opposite positions through the central axis of the chamber 1. The optical path of the laser beam L is set at the same height as that of the optical path of the laser beam L used for radical density measurement. The transmission windows 6A and 6B have the same arrangement as that of the ultraviolet light transmission windows 5A and 5B described in the first embodiment, so no pollutant attaches to them. More specifically, the transmission windows 6A and 6B may be heated to a high temperature of about 200°C to 400°C, or be formed of capillary plates each having a cylindrical structure with an aspect ratio of 3 or more. The capillary plates may have bottoms.

The gas temperature calculating section 53 obtains the attenuation amount spectrum of the laser beam L passing through the plasma on the basis of the light emission amount of the laser beam L input in advance and the output signal from the laser beam receiving section 52 and the radical absorption profile for the wavelength from the pattern of the attenuation amount spectrum, to calculate the temperature of the gas contained in the plasma P, and outputs the calculated temperature to a controller 44A. In the same manner as

in radical density measurement, a chopper is arranged in the optical path between the laser beam output section 51 and chamber 1. In the laser beam receiving section 52, the light reception amount obtained when the laser beam L is absent is subtracted from the light reception amount obtained when the laser beam L is present. Thus, the influence of background light is removed, so that an accurate temperature is calculated.

The controller 44A controls parameters for plasma generation, on the basis of output signals from a radical density calculating section 43 and the gas temperature calculating section 53, by considering the temperature error in the radial density measured by absorption spectroscopy.

When temperature correction of parameter control is performed in this manner, the process reproducibility can be further improved.

In this embodiment, the calculation result of the gas temperature calculating section 53 is output to the controller 44A. Alternately, the calculation result may be output to a radical density calculating section to perform temperature correction of the radical density. The corrected radical density may be output to a controller 44, and parameter control may be performed in the same manner as in the first embodiment.

Third Embodiment

Fig. 3 is a diagram for explaining an example

of a high-frequency plasma CVD apparatus according to the third embodiment of the present invention. Fig. 3 shows a section perpendicular to the central axis of a chamber 1. The same constituent elements as those shown in Fig. 1 are denoted by the same reference numerals. For the descriptive convenience, Fig. 3 shows an X-Y coordinate system having the center of the chamber 1 as the origin.

In this embodiment, a plurality of optical paths of ultraviolet light UV used for radical density measurement are set on a plane parallel to the stage surface of a susceptor 2. For example, as shown in Fig. 3, when the respective optical paths are to be set parallel to the X-axis, the absolute values of the Y-coordinates of the respective optical paths are set to be different from each other.

Input mirrors 61A, 61B, 61C, 61D, 61E, 61F, and 61G which reflect UV output from a hollow cathode lamp 41 and guide it to the corresponding optical paths so that the ultraviolet light UV passes through the respective optical paths, output mirrors 62A, 62B, 62C, 62D, 62E, 62F, and 62G which reflect the ultraviolet light UV passing through the respective optical paths and guide it to an ultraviolet light-receiving section 42, and ultraviolet light transmission windows 5 arranged on the respective optical paths are provided. The reflection surfaces of the input mirrors 61A to 61G

and of the output mirrors 62A to 62G are sequentially rotated so that the ultraviolet light sequentially passes through the respective optical paths. Thus, the plurality of optical paths can be set by time division.

The radical density calculated from the ultraviolet light UV passing through each optical path represents the integral value of the radical density on the optical path. Hence, assuming that the radicals are distributed concentrically around the central axis of the chamber 1, the radical densities of the respective beams of the ultraviolet light UV passing through the plurality of optical paths may be obtained and subjected to Abel conversion, so that a two-dimensional radical density distribution can be obtained. Since Abel conversion can be applied to a cylindrical shape, in this case, the shape of the chamber 1 is preferably cylindrical. Also, the number of optical paths equal to or larger than the amount of the resolution of the radical density distribution or more is necessary.

Parameter control for plasma generation is performed two-dimensionally on the basis of the obtained radical density distribution, so that the process reproducibility can be further improved. To perform parameter control for plasma generation two-dimensionally, for example, a plurality of gas introducing ports for introducing source gases into the chamber 1 are formed in the radial direction of the

chamber 1, so that the gas flow rates for the respective gas introducing ports can be controlled individually. Also, a plurality of heaters to be incorporated in the susceptor 2 are arranged concentrically. The temperatures of the respective heaters should be able to be controlled individually.

For example, assume that as a result of Abel conversion, a high-density radical density distribution is obtained at the central portion of the chamber 1, as shown in Fig. 5A. In this case, control is performed to decrease the flow rate of the gas toward the central portion of the chamber 1, as shown in Fig. 5B, so that the closer to the peripheral portion, the larger the gas flow rate. Thus, the radical density distribution becomes uniform, as shown in Fig. 5C.

A plurality of optical paths can be set by frequency division. In this case, choppers (modulators) 63A, 63B, 63C, 63D, 63E, 63F, and 63G which perform CW modulation (Carrier Wave modulation) for the ultraviolet light UV are arranged on the respective optical paths. The modulation frequencies of the choppers 63A to 63G are different from each other. As the input mirrors 61A to 61G, those which reflect part of the ultraviolet light and transmit the remaining ultraviolet light are used. The ultraviolet light UV which has passed through each optical path has a different carrier wave frequency. Thus, in the ultraviolet light-receiving section 42, the

ultraviolet light UV is separated by the carrier wave frequency. The radical densities are obtained from the respective separated beams of the ultraviolet light, and are subjected to Abel conversion, so that a two-dimensional radical density distribution can be obtained.

If a plurality of ultraviolet light transmission windows for radical density measurement are arranged in the axial direction (Z direction) of the chamber 1, and the radical density distribution in the Z direction is measured, a three-dimensional radical density distribution can be obtained. When parameter control for plasma generation is performed based on this radical density distribution, the process reproducibility can be further improved.

In the same manner as in the case described above wherein the two-dimensional radical density distribution is measured, a plurality of optical paths may be set for a laser beam L used for gas temperature measurement on a plane parallel to the stage surface of the susceptor 2 by time division or frequency division. The two-dimensional gas temperature distribution may be obtained from the laser beam L passing through the respective optical paths. The parameters for plasma generation may be controlled by considering the temperature error of the two-dimensional radical density distribution. To cause the laser beam L to pass through

the respective optical paths, mirrors or/and choppers may be used in the same manner as in radical density measurement.

Furthermore, a three-dimensional gas temperature distribution may be obtained, and the parameters for plasma generation may be controlled by considering the temperature error of the three-dimensional radical density distribution described above.

Fourth Embodiment

According to the fourth embodiment of the present invention, the electron temperature of a plasma P is estimated from the radical density measured in the first embodiment. Parameters for plasma generation are controlled such that the estimated electron temperature becomes close to a preset value.

For example, SiH_4 and SiF_4 decompose in accordance with the following reaction formulae. Figures in parentheses indicate dissociation energies.

(1) $SiH_4 \rightarrow SiH_3 + H$ (8.75 eV)

$SiH_4 \rightarrow SiH_2 + 2H$ (9.47 eV)

$SiH_4 \rightarrow SiH + 3H$ (9.47 eV)

$SiH_4 \rightarrow Si + 4H$ (10.33 eV)

(2) $SiF_4 \rightarrow SiF_3 + F$ (7.25 eV)

$SiF_4 \rightarrow SiF_2 + 2F$ (4.6 eV)

$SiF_4 \rightarrow SiF + 3F$ (6.8 eV)

$SiF_4 \rightarrow Si + 4F$ (6.0 eV)

As is apparent from the above reaction formulae, to decompose SiH_4 and SiF_4 to Si, high-energy electrons are necessary. Accordingly, the electron energy, i.e., the electron temperature can be estimated by measuring the behavior (magnitude of the density) of the Si radicals. As described above, the electron temperature is a parameter that is very significant in determining dissociation.

<u>Fifth Embodiment</u>

According to the fifth embodiment of the present invention, parameters for plasma generation are controlled to decrease the Si radical density measured in the first embodiment.

Si has a high reaction constant, and accordingly reacts as:

$$Si + SiH_4 \rightarrow Si_2H_4$$

$$Si + SiF_4 \rightarrow Si_2F_4$$

to generate high-order molecular radicals one after another. Accordingly, information on the behavior of high-order radicals can be obtained by measuring the density of the Si radicals. The high-order radicals generate dust and particles. Therefore, when control is performed to decrease the Si radical density, generation of high-order radicals is suppressed, and dust or the like can be prevented.

<u>Sixth Embodiment</u>

The present invention can also be applied to a

high-frequency plasma etching apparatus. An embodiment of the high-frequency plasma etching apparatus will be described as the sixth embodiment.

To etch an Si thin film or SiO_2 thin film, Cl_2 or C_xF_y (e.g., CF_4, C_4F_8, or C_5F_7) is used as an etching gas. At this time, the following reactions take place on the thin film:

$$Si + Cl_2 \rightarrow SiCl_2 \text{ or } Si + 4Cl \rightarrow SiCl_4$$

$$SiO_2 + CF_2 \rightarrow SiF_2 + CO_2$$

By-products generated in these reactions are $SiCl_2$, $SiCl_4$, SiF_2, and SiF_4. These by-products decompose in the plasma during the etching process to generate Si radicals. Therefore, in the etching process, when the Si radical density is measured and parameters for plasma generation are controlled, the process reproducibility and etching characteristics can be ensured and controlled.

The above embodiments exemplify high-frequency plasma apparatuses. The present invention can also be applied to any plasma apparatus such as a capacitive coupling type plasma apparatus, induction coupling type plasma apparatus, or ECR plasma apparatus. Note that such apparatus is aimed at generating a plasma which uses a gas containing at least Si or a plasma with which by-products containing at least Si are generated from a solid surface.

The present invention is not limited to a

process using a plasma, but can also be applied to a process in which a gas dissociates in an atmosphere to generate Si. For example, the present invention can be applied to a CatCVD or a CVD utilizing a catalyst. The present invention is not limited to a process using a gas, but can also be applied to, e.g., sputtering.

The present invention can also be applied to a nitriding process containing N_2 gas for an Si substrate (layer) or SiO_2 film, or an oxidizing process containing O_2 gas for an Si substrate (layer). In the nitriding process or oxidizing process, the present value of N radical or O radical density directly contributing to the reaction can be measured, and control operation can be performed to make the density constant. Thus, a sufficient effect can be obtained. To measure the N radical density, vacuum ultraviolet light having a wavelength of approximately 120 nm is used. To measure the O radical density, vacuum ultraviolet light having a wavelength of approximately 130 nm is used. Regarding an N-based gas, for example, the light emission spectrum of N radicals is measured. The rotational temperature can be obtained from the intensity distribution of the envelopes of the light emission spectrum. In an equilibrium state, the rotational temperature coincides with a translational temperature. Hence, the N radical density can be temperature-corrected with the obtained gas temperature.

To measure the F or H radical density, ultraviolet light having a wavelength of approximately 96 nm or 121.6 nm may be used, and control operation may be performed such that the respective densities become constant. This also applies to C radicals. Control operation based on the result of density measurement is possible.